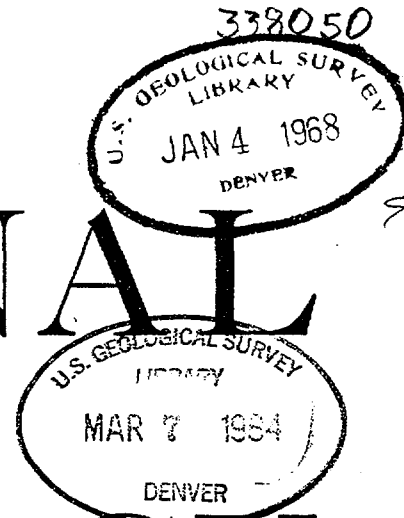


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# THE RAINY CREEK ALKALINE-ULTRAMAFIC IGNEOUS COMPLEX NEAR LIBBY, MONTANA I: ULTRAMAFIC ROCKS AND FENITE<sup>1</sup>

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## ABSTRACT

The Rainy Creek complex represents a composite of successive intrusions of igneous rocks emplaced into the Precambrian Belt Series, probably in middle Cretaceous time. The succession began with the emplacement of a body of coarse-grained biotite pyroxenite with a core of coarse-grained biotitite, which is considered to have formed from the accumulation of alkalis and volatiles near the roof of the pyroxenite pluton. Nodules in the biotitite appear to be xenoliths of altered ultramafic rock. Following this igneous phase, magnetite pyroxenite intruded a zone of weakness between the biotite pyroxenite and the Belt Series, forming a ring dike surrounding the inner pyroxenite body. All of the ultramafic rocks are considered to be products of fractional crystallization of a common parent magma. Available mineralogic and experimental data suggest that the biotitite and biotite pyroxenite were emplaced under high  $p_{H_2O}$  and  $f_{O_2}$ - $T$  conditions. Fenitizing ions, which probably originated in deep-seated ijolite or carbonatite, have altered part of the Belt Series adjacent to the magnetite pyroxenite.

## INTRODUCTION

### PURPOSE, SCOPE, AND METHODS

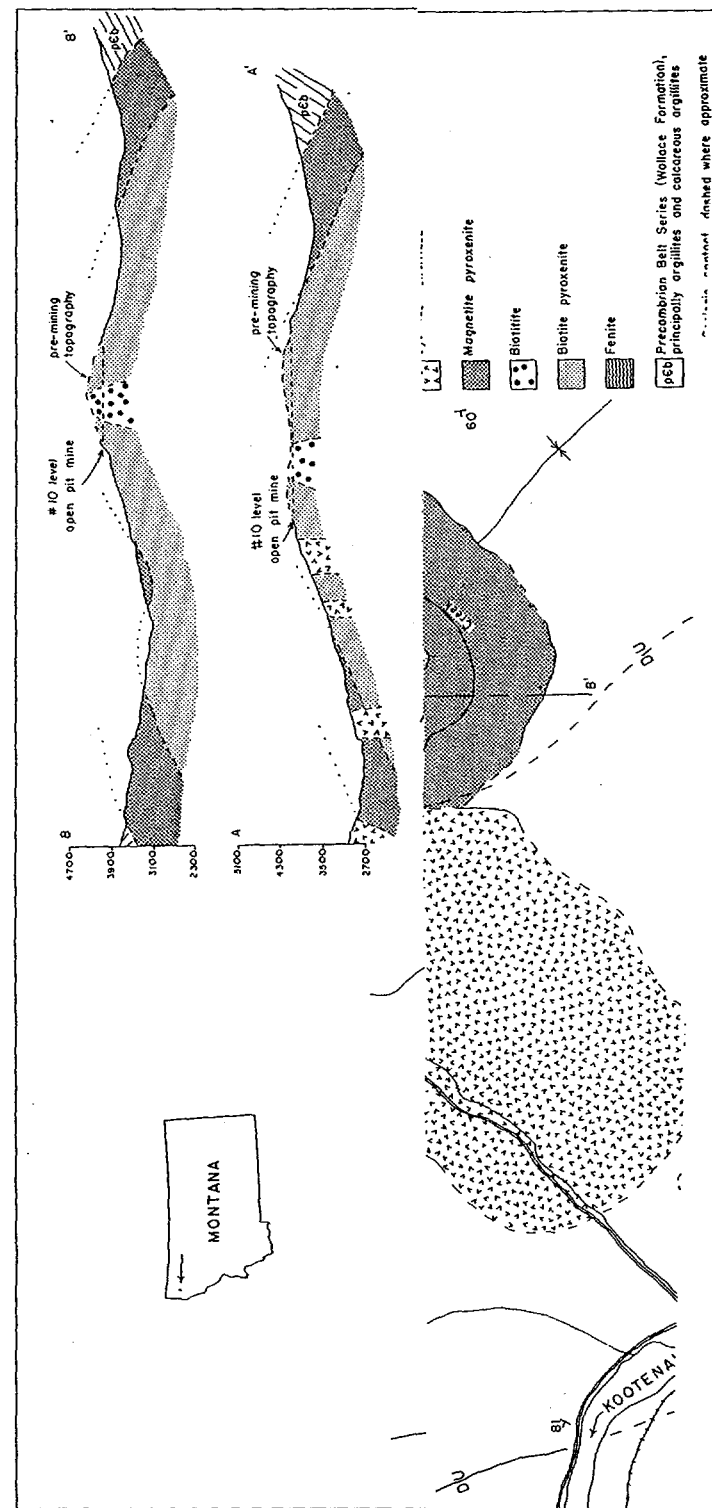
This is a geologic, petrologic, and geochemical study of a body of ultramafic rocks near Libby, Montana. Consanguineous alkaline rocks will be the subject of a later paper. This zoned, composite body, known herein as the Rainy Creek pluton, contains a large mass of altered biotite pyroxenite that has been the major source of commercial "vermiculite" in the world. For this reason and also because this area has yielded minerals of unusual interest, these deposits are world famous. Earlier investigations, which have been brief and were hindered by an incompleteness of outcrop and an inaccessibility of most of the area, suggested a mineralogic and structural simplicity now known to be unreal. The present investigation, favored by the availability of time, both in the laboratory and field, and data derived from many new drill holes and artificial exposures have shown that the pluton and related bodies are very complex.

<sup>1</sup> Manuscript received September 28, 1966.

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Thus, the purpose of this report is to document the geology, petrology, and geochemistry of these rocks and to propose an origin for them. As this complex has many affinities with other well-known alkaline-ultramafic centers, particularly those associated with carbonatite, the writer hopes that this study will contribute toward further understanding of the general problems of the origins of such rocks.

Most of the field work was done during the summer months of 1962 and 1964. The writer also benefited from employment at Rainy Creek by the Zonolite Company in 1960 and by his mapping in this general region for the Montana Bureau of Mines and Geology in 1961. The general geology of the area was plotted on aerial photographs and transferred to U.S. Forest Service planimetric map 815-4-2. Zonolite Division topographic and property maps and J. Neils Lumber Company planimetric maps provided the base for the geologic map (fig. 1). Geologic maps of the Zonolite open pit mine (a part of which is shown in fig. 2) and of exploration adits, not included in this paper, were prepared at a scale of 1:600 on base maps surveyed by the writer with the assistance of employees of the Zonolite Divi-



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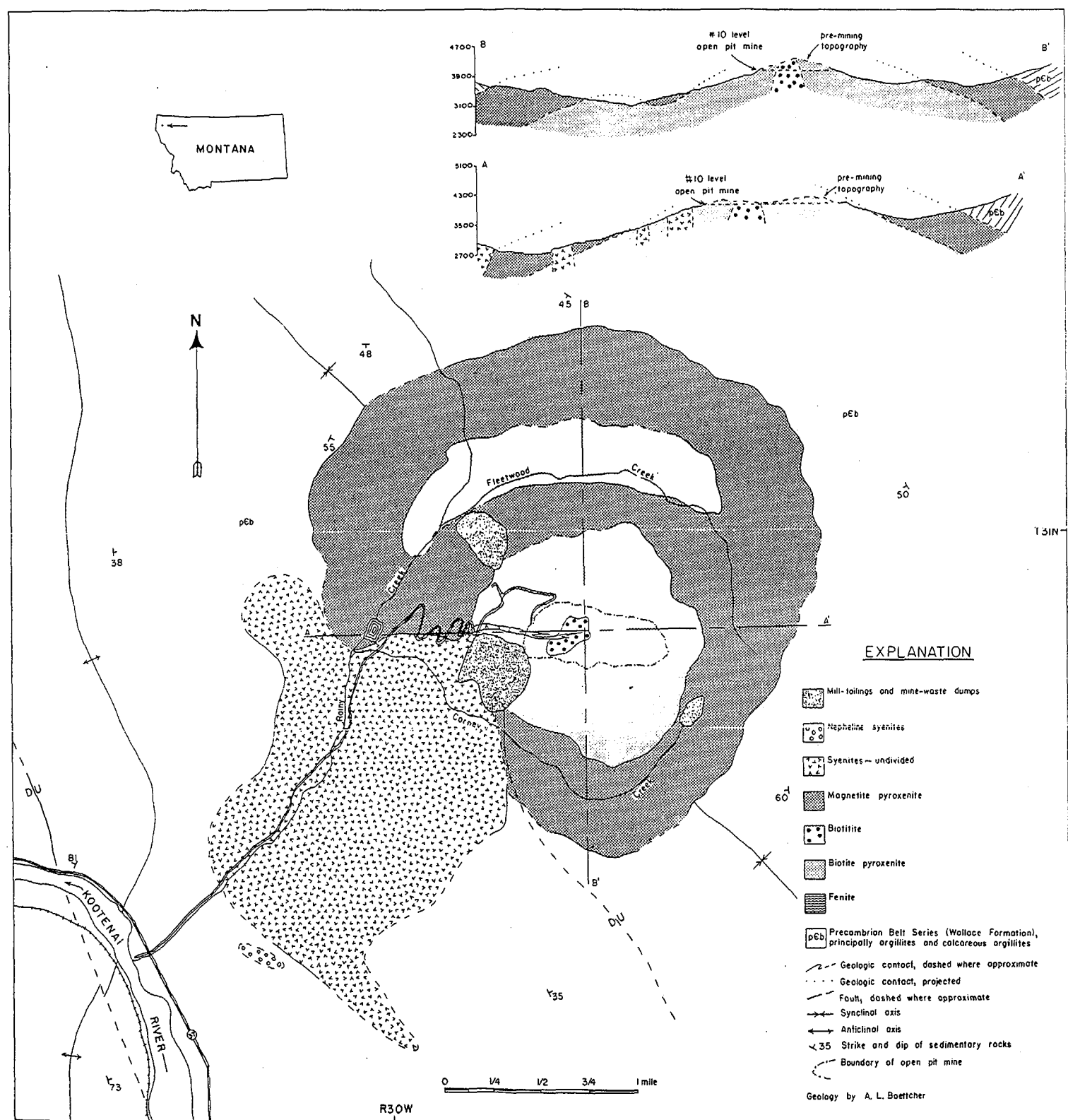


FIG. 1.—Geologic map and interpretative cross sections of the Rainy Creek complex

sion. The magnetic survey map (fig. 3) was constructed from data obtained with an Edgar Sharpe ES-180 magnetometer with a reported accuracy of 5  $\gamma$ .

The term "vermiculite" will be used in this report to refer to any sheet silicate mineral, including vermiculite and hydrobiotite, that will exfoliate upon heating. The term vermiculite will be used to identify

the mineral species as defined by Warshaw and Roy (1961). Hydrobiotite herein refers to a regular heteropolytypic 1-1 biotite-vermiculite (see Bloss, 1966). Rock names and textural terms follow the definitions listed in Johannsen's volumes or in the *A.G.I. Glossary of Geology and Related Sciences*, the latter governing where a conflict exists. The adjective "alkaline" will be used,

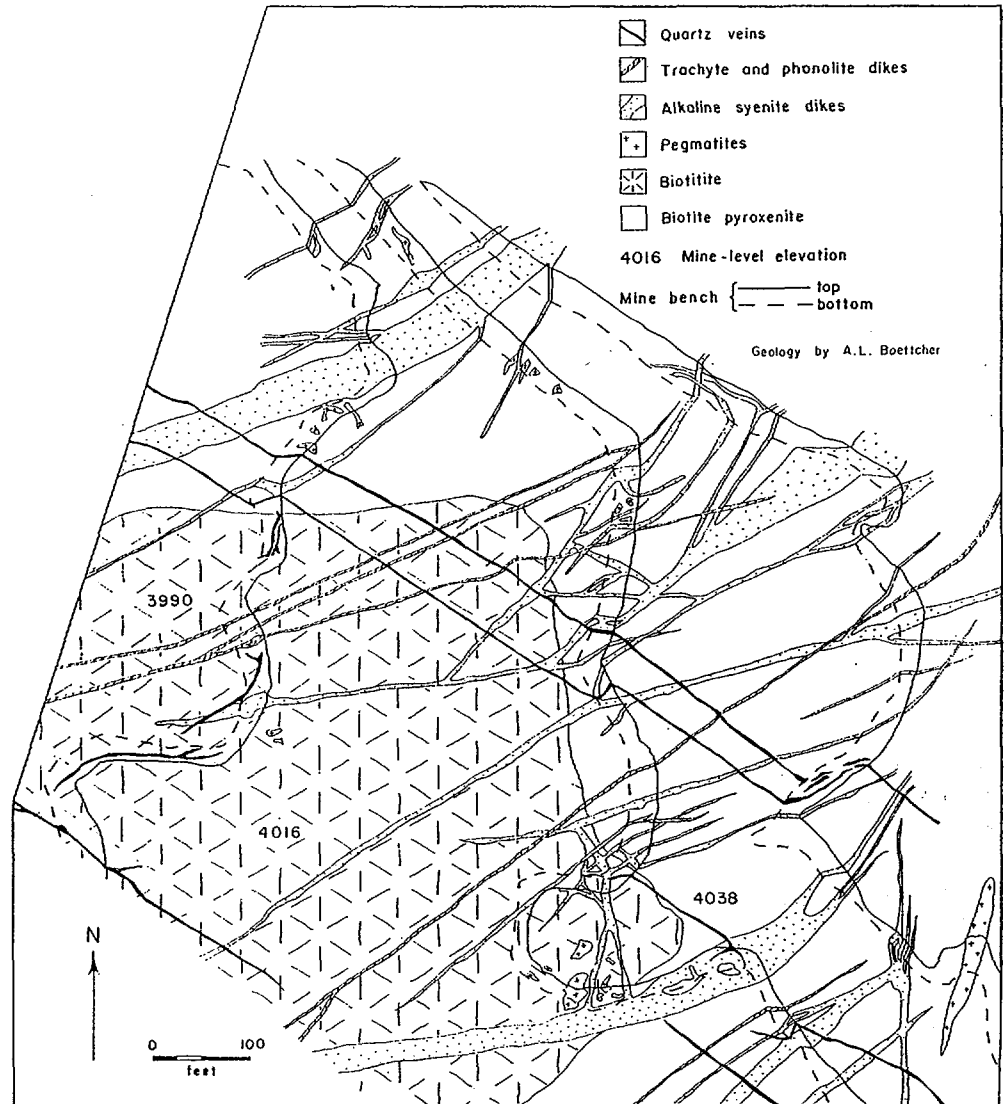


FIG. 2.—Geologic map of part of the open pit mine at the Rainy Creek complex

when referring to rocks, in the sense proposed by Shand (1922). Such alkali-rich rocks are characterized by Al deficiency (as evidenced by the presence of minerals such as aegirine), by Si deficiency (as evidenced by feldspathoids), or by both.

#### PREVIOUS RELATED WORK

E. S. Larsen and J. T. Pardee, who visited the district several times between 1911 and 1927, were the principal early investiga-

tors of the Rainy Creek complex. Goranson (1927) reported on the mineralogy of aegirine collected by Larsen from "syenite" (fensite) near the north border of the pluton. Descriptions of the general nature of the intrusion and the petrology of some of the rock types were published by Larsen and Pardee in 1929 (Larsen and Pardee, 1929; Pardee and Larsen, 1929). Because natural exposures are few and large-scale mining operations were only in the early

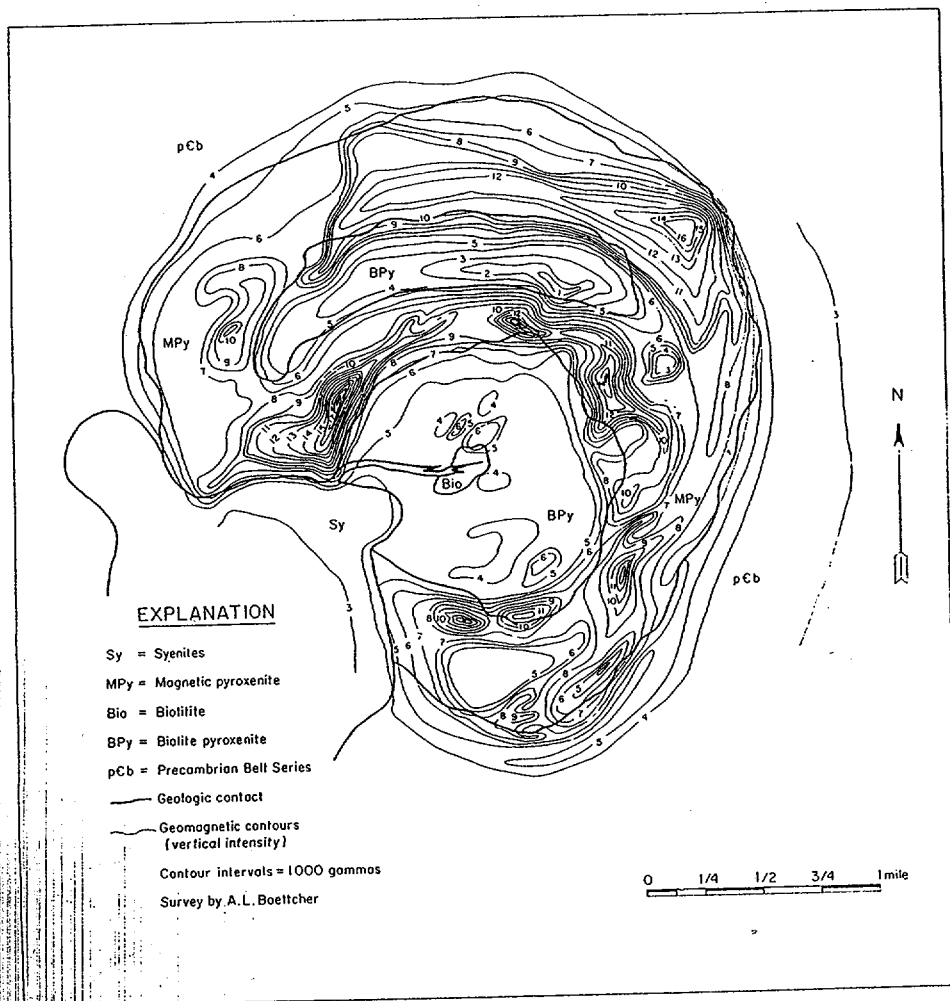


FIG. 3.—Geomagnetic survey map of the Rainy Creek complex

stages of development, their investigation was considerably restricted.

Succeeding investigations of the complex have emphasized mineralogy or have been of a very general nature. Gruner (1934), on the basis of X-ray studies, first proposed the name "hydrobiotite" for the layer silicate found in abundance at Rainy Creek. Kujawa (1942) reported on the genesis and mineralogy of the "vermiculite" deposits. A brief description of the mining operation and general geology of the igneous complex and surrounding country rock was provided by Perry (1948). Bassett (1959) discussed the geology of the deposits and performed experimental studies of the "vermiculite." Beer (1960) and Johns (1960), in mapping the regional geology of the Kootenai area of Montana, described the rocks of the Belt Series surrounding the Rainy Creek complex. Theses submitted by the writer (Boettcher, 1963, 1966a) served as a basis for this paper. The results of an experimental investigation of the origin of vermiculite and hydrobiotite at Rainy Creek have been presented elsewhere (Boettcher, 1966b).

#### REGIONAL DISTRIBUTION OF IGNEOUS ROCKS

The Rainy Creek pluton is the largest alkaline-ultramafic igneous body in the region and is probably of Cretaceous age. Two bodies of syenite (Johns, 1959, p. 18; 1960, p. 20-21) and one of syenite and pyroxenite (Johns, 1959, p. 18), which also occur in this region, may be related genetically to the Rainy Creek pluton, but these bodies are very small and have not been examined in detail. With these exceptions, the Rainy Creek complex contains the only known bodies of ultramafic or alkaline rocks in northwestern Montana and contiguous parts of Canada and Idaho. The Ice River complex described by Allan (1914) is about 200 miles north of Libby. The famed Montana potassic provinces lie east of the Rocky Mountains and are of Tertiary age. Extending from the Alaska-Yukon border to central British Columbia is a belt of ultramafic complexes, but in these bodies zoning is

scarce, dunite is common, orthopyroxene greatly predominates over clinopyroxene, and alkaline rocks are unknown (Noble and Taylor, 1960).

Numerous other small bodies of igneous rocks, ranging in composition from acidic to basic, in age from Precambrian to Laramide(?), and in form from stocks to dikes and sills, are distributed throughout the region. The largest of these bodies is a stock of quartz monzonite 20-square miles in area about 15 miles southwest of the Rainy Creek area (Gibson, Campbell, and Jenks, 1938; Gibson, 1948). Although the relationship between these rocks is unknown, their widespread areal distribution throughout northwestern Montana suggests to this writer that they are genetically unrelated to the rocks of the Rainy Creek complex.

#### REGIONAL STRUCTURE AND STRATIGRAPHY

The igneous rocks of the Rainy Creek district have intruded Precambrian sedimentary rocks of the Belt Series (fig. 1). At the surface, the intrusion is enclosed by rocks of the upper beds of the Wallace formation, which consist of about 15,000 feet of heterogeneous argillites and dolomitic and calcareous argillites. For descriptions of detailed regional lithology and stratigraphy, the reader is referred to the works of Gibson (1948), Beer (1960), and Johns (1960).

The Belt Series in the vicinity of Rainy Creek is folded into broad north-northwest trending synclines and anticlines. The pluton lies along the axis of one of these asymmetric synclines, which appears to plunge southeast and terminate 1 mile or less from the pluton. An alternate interpretation is that the strata have centripetal dips, except near the synclinal axis southeast of the complex, resulting from the emplacement of the pluton, but later modified by regional tectonism. Two high-angle faults, which post-date the folding, have been mapped near Rainy Creek. One of them trends north-northwest and intersects the south side of the complex near Carney Creek. Nevertheless, the other syenite and pyroxenite plutons mentioned in the previous section do

not appear to be spatially related to faults or folds; and this suggests that the Rainy Creek complex is genetically unrelated to these structural features.

#### GENERAL GEOLOGY OF THE IGNEOUS COMPLEX

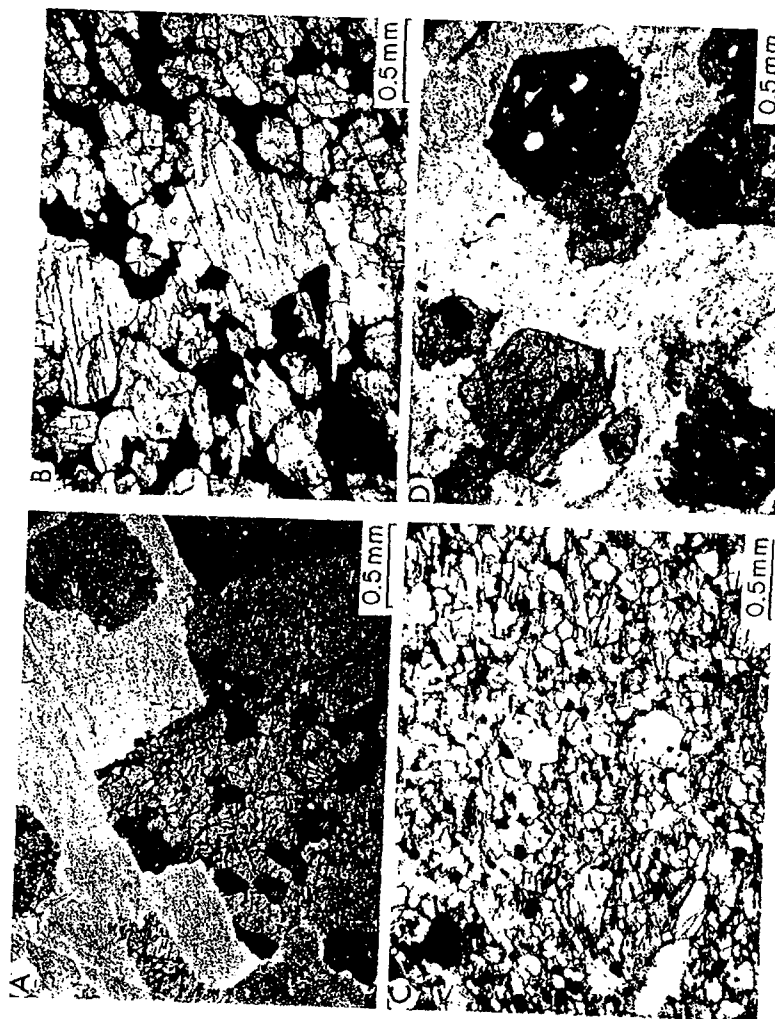
##### GENERAL FEATURES AND STRUCTURE OF THE IGNEOUS BODIES

The Rainy Creek complex consists mainly of a concentrically zoned, composite pluton, crudely circular in plan, composed mostly of zones of magnetite pyroxenite, biotite pyroxenite, and biotitite, arranged in inward succession. It also contains an irregularly shaped syenite body, which lies along the southwest side of the ultramafic pluton and extends into the magnetite pyroxenite and biotite pyroxenite zones. A small outlying body of nepheline syenite lies about 500 feet southwest of this syenite body. Many narrow dikes of members of the alkaline syenite and trachyte-phonolite clans, alkaline pegmatites, alkaline granite, and late-stage quartz-rich veins cut all of the earlier rocks.

Because the elevation of Fleetwood Creek on the north side of the complex is less than that of Carney Creek on the south, the shape of the ultramafic body is distorted in plan view. Contours around the pluton, however, would be nearly circular with the biotitite body occupying a position near the center of the contoured body. The central core of biotitite and the surrounding zone of biotite pyroxenite are expressed topographically as a resistant dome. This dome is bounded by deep stream channels that coincide with the outer ring of less resistant magnetite pyroxenite. Although mostly con-

cealed by till and a dense overgrowth of brush and trees, the contact between magnetite pyroxenite and rocks of the Belt Series is generally expressed by an abrupt increase in slope and a decrease in the density of coniferous vegetation away from the igneous rocks. The bodies of syenite and nepheline syenite have no obvious topographic expression. A large open pit mine near the center of the pluton exposes much of the biotite pyroxenite and biotitite.

The zone of fine-grained magnetite pyroxenite is later than and surrounds the inner zone of pyroxenite to form an outward-dipping body. This body is herein considered to be a ring dike because the contact with the inner pyroxenite zone is sharp and many dikes and apophyses of magnetite pyroxenite transect the inner pyroxenite. Inasmuch as the borders of the main magnetite pyroxenite body are poorly exposed for most of their length, the attitude and, therefore, the true thickness is difficult to determine. The cross sections on plate 1 thus show the results as determined collectively from small isolated outcrops, from the relationship between outcrop pattern and topography, and from the data of the magnetic survey (fig. 3). Together, these data constitute evidence that, near the surface, the ring dike dips about 25 degrees outward, but extensive drilling or additional geophysical evidence will be required to substantiate this. The arcuate body of biotite pyroxenite in Fleetwood Creek is thus a window that has become exposed after the stream eroded the overlying magnetite pyroxenite. If the outer contact of the pluton were projected upward at the attitude thus suggested, the roof would have



#### PLATE 1

A, Photomicrograph of contact between biotite pyroxenite and biotitite; strongly resorbed biotite and optically continuous patches of microcline in diopside—plane light.

B, Photomicrograph of magnetite pyroxenite (M-39); clinopyroxene, apatite, and magnetite—plane light.

C, Photomicrograph of magnetite pyroxenite dike (RCMD-128); magnetite in clinopyroxene, biotite, and apatite—plane light.

D, Photomicrograph of fenite (RCF-216); euhedral schorlomite (dark) and aggregate pseudomorphs of andradite, sphene, and magnetite in potash feldspar matrix—plane light.



A



B

been less than 2,000 feet above the present surface. Coupled with petrographic evidence to be presented in a following section, this suggests that the exposed igneous rocks represent the upper part of the pluton. The contacts probably become more nearly vertical with depth, in accord with a dome-shaped configuration proposed for the outer zone.

Because the magnetite pyroxenite everywhere forms the outer boundary of the body of biotite pyroxenite—except where the latter is bounded by the syenite body—and because no other annular fracture zones or screens of country rock occur within or immediately beyond the pluton, the intrusion of the ring dike of magnetite pyroxenite probably did not occur along fractures created by forceful emplacement of the biotite pyroxenite. Rather, the magnetite pyroxenite probably intruded a zone of weakness between country rock and pyroxenite core following movement of the latter and created a ring dike. The effects of such movement may not have extended to the surface and have given rise to volcanic activity, but explosive volcanism has occurred at many similar alkaline centers, probably the result of the high volatile content of these magmas. Such activity at Rainy Creek would have been removed by erosion, but the trachyte and phonolite dikes indicate at least shallow, if not extrusive, igneous activity.

Alternate interpretations of the origin of the configuration of the zones of ultramafic rocks include differentiation in place. However, if crystallization proceeded inward, beginning with magnetite pyroxenite, it would be difficult to explain the dikes and apophyses of magnetite pyroxenite that

transect the biotite pyroxenite. In addition, the pyroxenes in the magnetite pyroxenite are more Fe-rich than those in the biotite pyroxenite, which suggests that they crystallized later. If crystallization proceeded outward, it is unlikely that such a large reduction in grain size would accompany the transition from biotite pyroxenite to magnetite pyroxenite.

#### AGE OF THE IGNEOUS ROCKS

Field relationships indicate only that the igneous rocks cut strata of the Wallace formation and are covered by Pleistocene till. Radiogenic dating by the Sr-Rb method on fresh biotite (sample RCB-12) from the biotite core yielded an age of 94 m.y. (S. S. Goldich, personal communication, 1965). Inasmuch as the sample consisted entirely of biotite, internal readjustment of Sr and Rb should have been slight, and this determination, therefore, has the advantage of a whole-rock analysis.

The age of the complex was previously inferred to be Laramide (Perry, 1948; Beer, 1960; Johns, 1960) as have most igneous rocks of unknown age in western Montana. According to the revised time scale of Holmes (1960), an age of 94 m.y. would be lower Upper Cretaceous. However, Laramide age is defined by Eardley (1962, p. 295) as Montana time (upper Upper Cretaceous) through Eocene time, and by Gilluly (1963, p. 150) as beginning in Montana during Turonian time (middle Upper Cretaceous). The Rainy Creek complex thus appears to be pre-Laramide in age, in accord with the observation that alkaline magmatism is indigenous to epeirogenic continental environments (Bailey, 1964).

#### PLATE 2

A, Apatite-rich pyroxenite mass (center, V-shaped) cutting lighter colored biotite pyroxenite—white, disseminated spots are apatite.

B, Dikes of magnetite pyroxenite and syenite cutting coarse-grained biotite pyroxenite. The head of the rock pick rests on biotite pyroxenite; the handle rests on magnetite pyroxenite. Note dark, vertical magnetite segregations near center between syenite dikes.



ULTRAMAFIC ROCKS  
BIOTITE PYROXENITE

Observed in plan, 18 per cent of the Rainy Creek complex is biotite pyroxenite. It forms a circular body almost completely enclosed by magnetite pyroxenite. The absence of cross-cutting relationships between the pyroxenite and biotite core suggests that they are contemporaneous, but all of the other igneous rocks in the complex, except for those in the outlying body of nepheline syenite, transect these two bodies. Therefore, the inner body of pyroxenite and the biotite body appear to be the oldest exposed intrusive rocks within the district. As this pyroxenite contains all of the economic "vermiculite" deposits, it is well exposed by the mining operations.

Clinopyroxene and "vermiculite" constitute nearly all of this rock, but the two are present in all proportions, and apatite is a common accessory. Unaltered biotite is irregularly distributed in small areas within the pyroxenite. Although a wide range in the proportions of "vermiculite" and pyroxene occur from place to place, mining records indicate an average "vermiculite" content of about 30 weight per cent. In grain size, this pyroxenite ranges from less than 1 cm. to about 1 m., but most of the grains are 4 cm. or more in maximum dimension. Although no regular zoning, either laterally or vertically, has been noted, the largest crystals of pyroxene occur adjacent to the biotite core. Contrary to the statement of Bassett (1959, p. 285), most of the pyroxene and "vermiculite" show no obvious preferred orientation.

On the basis of experimental work and chemical analyses, the writer (Boettcher, 1966b) concludes that both the vermiculite and hydrobiotite, which constitute the "vermiculite" in this pyroxenite, have formed from biotite, the former being a weathering product, the latter a product of hydrothermal alteration. No reaction relationship has been observed between the biotite and pyroxene, and they appear to be a eutectic pair. As noted in the following

section, however, biotite shows pronounced resorption near the contact with the biotite core.

Some of the "vermiculite" and biotite are concentrated in tabular to irregularly shaped pyroxene-bearing bodies that transect the normal pyroxenite. No evidence of replacement of the surrounding pyroxenite was noted, and these bodies are considered to result from late surges of volatile-rich magma. In many of these bodies, the "vermiculite" or biotite shows a strong preferred orientation with the basal faces parallel to the walls.

The apatite occurs as pale-green prisms averaging 1-2 cm. long, but it attains lengths of 10 cm. in some of the coarser-grained varieties. Apatite is the earliest mineral to crystallize throughout this pyroxenite body and is poikilitically enclosed in the pyroxene grains and in the books of biotite and "vermiculite." The apatite is irregularly distributed, but it occurs mostly with "vermiculite" and is a very minor constituent of the "vermiculite"-barren pyroxenite. The association of apatite and "vermiculite" or biotite has been reported in other bodies of biotite pyroxenite, for example, the Loolekop, Transvaal complex (Gevers, 1948, p. 148) and the Shawa, Rhodesia complex (Johnson, 1961, p. 131). At Rainy Creek, apatite locally forms as much as 20 per cent of the pyroxenite, but the average value is estimated as 2 per cent. High concentrations of apatite occur in many of the late "vermiculite"-rich bodies (pl. 2, A).

Minerals other than pyroxene, "vermiculite," biotite, and apatite are scarce in this pyroxenite, but incipient tremolitization of the pyroxene is widespread throughout this rock and appears to be deuteric and earlier than tremolitization that is related to the emplacement of the later dikes and veins. Minor amounts of sphene have been observed in some samples, and a few microscopic grains of carbonate and zircon were detected in the panned concentrate of a 2-lb. sample of the pyroxene. Feldspar is present in some of the apatite-rich rock and occurs

as crystals as much as 3 cm. in diameter, which poikilitically enclose euhedral crystals of the pyroxene. Most of the feldspar is plagioclase with a composition of  $Ab_{95}$  determined by the method of Schairer, Smith, and Chayes (1956), but some microcline is also present. An analogous occurrence is reported at Loolekop (Gevers, 1948, p. 147) where isolated feldspar crystals occur within

the unaltered biotite in this pyroxenite as the same as those for the biotite in the biotite (see table 4). The apatite is fluorapatite as indicated by  $n_D = 1.642$  and  $n_E = 1.639$  (Deer, Howie, and Zussman, 1962, p. 331). The pyroxene is mostly emerald-green chrome diopside. A chemical analysis of the optical properties of a representative specimen collected about 110 feet due east

TABLE 1  
CHEMICAL ANALYSIS,\* NORM, AND MODE OF  
BIOTITE PYROXENITE (RCPY-64)

Analysis		C.I.P.W. Norm†		Mode (Weight Per Cent)‡	
SiO <sub>2</sub> .....	44.87	ne	1.65	Apatite	2.5
Al <sub>2</sub> O <sub>3</sub> .....	6.35	lc	6.85	Diopside	60.0
TiO <sub>2</sub> .....	0.88	or	11.34	"Vermiculite"	37.5
Cr <sub>2</sub> O <sub>3</sub> §.....	0.03	an	6.40		
Fe <sub>2</sub> O <sub>3</sub> .....	4.96	ap	2.59		
FeO.....	2.79	il	1.75		
NiO.....	0.00	mt	7.02		
CuO§.....	0.11	hm	0.15		
ZnO§.....	0.05	fo	16.71		
MnO.....	0.09	di	45.12		
MgO.....	17.26				
CaO.....	13.61				
SrO§.....	0.04	di (sen	20.92		
BaO§.....	0.17	wo)	24.20		
Na <sub>2</sub> O.....	0.35	D.I.¶	19.84		
K <sub>2</sub> O.....	3.26	C.I.#	51.52		
H <sub>2</sub> O+.....	2.55				
H <sub>2</sub> O-.....	1.51				
P <sub>2</sub> O <sub>5</sub> .....	1.05				
Total.....	99.93				

\* Analyst: C. O. Ingamells.

† Norm was calculated after subtracting H<sub>2</sub>O+ and H<sub>2</sub>O- and recalculating total to 99.93.

‡ Obtained by weighing constituent minerals.

§ Spectrometric analyses by N. H. Suhr.

¶ Differentiation index.

# Crystallization index.

"marked concentrations of apatite and vermiculite" in the pyroxenite. Within the open pit mine, about 600 feet southeast of the east end of the biotite body, is a small area in which the pyroxenite contains abundant calcite and dolomite in addition to feldspar.

A chemical analysis, norm, and mode of a sample considered to be representative of most of the altered biotite pyroxenite are listed in table 1. The optical properties of

of the biotite body appear in table 2. The ratios of ions were calculated according to the procedure of Hess (1949).

The composition of the pyroxenes differs slightly from place to place within the biotite pyroxenite, and these changes are reflected in the color—darker green indicating more Fe than is contained in the typical emerald-green material. The discriminative curves of Hess (1949) and Muir (1951) were modified to fit the chemical



ical analyses and partial analyses of the pyroxenes from both pyroxenite bodies of the Rainy Creek pluton listed in tables 2, 8, and 9. These modifications were necessary because the  $\text{Fe}^{++}:\text{Fe}^{+++}$  ratio is unusually high in these pyroxenes, and they confirm the findings of Segnit (1953) that each 1.0 per cent of  $\text{Fe}_2\text{O}_3$  increases the refractive indices by about 0.003. With the revised

atomic ratio of Fe were those with accessory magnetite, but these do not include the magnetite-rich dikes which are considered in a following section on the magnetite pyroxenite.

## BIOTITITE

The biotitite core is well exposed in the open pit mine. In plan view it is an irregular-

TABLE 2

CHEMICAL ANALYSIS\* AND OPTIC PROPERTIES  
OF CLINOPYROXENE (P-100) FROM  
BIOTITE PYROXENITE

Analysis		Cations on the Basis of 6 Oxygens	
$\text{SiO}_2$	53.94	Si	1.969
$\text{Al}_2\text{O}_3$	0.76	Al <sup>IV</sup>	0.031
$\text{TiO}_2$	0.26	Al <sup>VI</sup>	0.002
$\text{Cr}_2\text{O}_3$	0.20	Cr	0.006
$\text{Fe}_2\text{O}_3$	1.13	$\text{Fe}^{++}$	0.031
$\text{FeO}$	1.91	$\text{Fe}^{+++}$	0.058
$\text{MnO}$	0.07	Mn	0.002
$\text{MgO}$	16.93	Mg	0.920
$\text{CaO}$	24.55	Ca	0.959
$\text{Na}_2\text{O}$	0.17	Na	0.012
$\text{K}_2\text{O}$	<0.01	K	.....
$\text{SrO}^\dagger$	0.04	Ti	0.007
$\text{BaO}^\dagger$	<0.01	Sr	.....
$\text{H}_2\text{O}^-$	0.03	Ba	.....
Total.....	100.00	O	6.000
$n_a = 1.678 \pm 0.001$		Perfect (100) parting	
$n_g = 1.684 \pm 0.001$		Hand specimen is emerald green	
$n_y = 1.702 \pm 0.001$		Non-pleochroic	
$2V_\gamma$ (calculated = $56.3^\circ$ )		.....	
$2V_\gamma$ (measured) = $56^\circ$		.....	
$ZAC = 41^\circ$		.....	

\* Analyst: C. O. Ingamells.

† Spectrometric analyses by N. H. Suhr.

curves, the compositions of thirty-six pyroxenes from the biotite pyroxenites and magnetite pyroxenites were determined from their optical properties. Determinations of the atomic ratio of Fe (i.e., the ratio  $\text{Fe}^{+++}:\text{Fe}^{++}:\text{Fe}^{+++} + \text{Fe}^{++} + \text{Mg}$ ) range from 0.08 to 0.12 in the normal rock and from 0.11 to 0.18 in the later bodies of apatite-rich pyroxenite. In these later bodies, the pyroxenes with the highest values of

ly shaped body with a northeast-trending long axis of about 1,450 feet and a maximum width of about 830 feet. Prior to mining, it cropped out near the highest point in the pluton at an elevation of 4,240 feet. It is now exposed in the lowest mine levels at an elevation of 3,855 feet. The biotitite consists almost entirely of coarse-grained biotite. This mica occurs in anhedral, rarely euhedral, books ranging from less than 1

cm. to about 1 m. in diameter, although most of it occurs in books 10 cm. or more in diameter. The books show no obvious preferred orientation.

Chemical analyses of two biotite samples are shown in table 3. Samples RCB-55 and RCB-12 were collected from the center and from near the western border of the

more abundant near the center than near the contact with the pyroxenite. Both intermediate microcline ( $\text{Or}_{94}[\text{Ab} + \text{An}]_6$ ) and albite ( $\text{Ab}_{95}$ ) are present; the latter appears to result from albitization of the former. The albite composition was determined by the method of Schairer *et al.* (1956) and the potash feldspar by X-ray methods using

TABLE 3

CHEMICAL ANALYSES\* AND NORMS OF BIOTITES FROM BIOTITITE

	RCSp-55	RCB-12	C.I.P.W. Norms†		
				RCSp-55	RCB-12
$\text{SiO}_2$	39.10	38.63	kp	15.05	14.71
$\text{Al}_2\text{O}_3$	13.30	13.08	lc	28.16	28.47
$\text{TiO}_2$	1.21	1.55	ne	1.11	1.25
$\text{Cr}_2\text{O}_3$	0.25	0.23	c	1.63	1.58
$\text{Fe}_2\text{O}_3$	2.56	2.50	an	0.65	0.95
$\text{FeO}$	7.23	8.75	il	2.41	3.10
$\text{NiO}$	0.02	0.02	mt	3.90	3.81
$\text{MnO}$	0.10	0.14	fo	39.52	36.63
$\text{MgO}$	21.55	19.94	fa	7.59	9.52
$\text{CaO}$	0.12	0.18	D.I.§	44.31	44.43
$\text{SrO}^\dagger$	< 0.005	0.005	C.I.	40.17	37.58
$\text{BaO}^\dagger$	0.35	0.45			
$\text{Na}_2\text{O}$	0.23	0.26			
$\text{K}_2\text{O}$	10.05	10.00			
$\text{Rb}_2\text{O}$	0.03	0.04			
$\text{H}_2\text{O}^+$	3.74	3.52			
$\text{H}_2\text{O}^-$	0.06	0.30			
$\text{P}_2\text{O}_5$	0.00	0.06			
F	0.35	0.30			
O = F	99.98	99.95			
	-0.18	-0.12			
Total.....	99.80	99.83			

\* Analyst: C. O. Ingamells.

† Norm was calculated after subtracting  $\text{H}_2\text{O}^+$ ,  $\text{H}_2\text{O}^-$ , and F and recalculating analyses to original totals.

‡ Spectrometric analyses by N. H. Suhr.

§ Differentiation index.

|| Crystallization index.

biotitite body, respectively. As the biotitite consists almost entirely of biotite, table 3 also shows the results of the analyses recast into norms. Optic properties and atomic ratios for the analyzed biotites appear in table 4.

Feldspar, a common but sporadic accessory in the biotitite, occurs as wedges up to about 8 cm. long between the mica books. The total feldspar content of the rock is estimated to be 2 per cent, but it is

the curves of Luth (unpublished data, 1965). Some of the albite appears to replace biotite, and it commonly contains a small amount of calcite.

Pyrite is a common accessory, but it is present in amounts less than 1 per cent. It occurs as fresh anhedral grains in the biotite and feldspars, being much more abundant near the center of the biotitite body. Calcite and riebeckite(?) are present in minor amounts in some samples, but these miner-

als appear to be secondary alteration products of the biotite. Apatite is almost entirely absent. Small alkaline pegmatites, which consist mostly of aegirine-augite and alkali feldspars and appear to have crystallized in situ, occur throughout the biotitite.

The contact between biotitite and biotite pyroxenite, for most of its length, is gradational over about 1-10 feet. Outward from

TABLE 4

OPTIC PROPERTIES AND HALF-CELL ATOMIC RATIOS\* OF BIOTITES FROM BIOTITITE

	RCSp-55	RCB-12
$n_a \pm 0.003$ .....	1.568	1.569
$n_g = n_r \pm 0.001$ .....	1.609	1.609
$n_r - n_a$ .....	0.041	0.040
$2V_a^\dagger$ .....	12°	11°
Pleochroism .....	$X < Y = Z^\ddagger$	Same as RCSp-55
Si .....	2.86	2.86
Al <sup>IV</sup> .....	1.13	1.14
Ti .....	0.07	0.09
Cr .....	0.01	0.01
Fe <sup>+++</sup> .....	0.14	0.14
Fe <sup>++</sup> .....	0.44	0.54
Mn .....	0.01	0.01
Mg .....	2.35	2.20
Ca .....	0.01	0.01
Na .....	0.04	0.04
K .....	0.93	0.94
Ba .....	0.01	0.01
OH .....	1.82	1.74
F .....	0.08	0.07
O .....	10.09	10.08

\* Calculated from analyzed  $H_2O$  using method of Foster, Wones, and Eugster (1963).

† Optic angles were measured using the procedure of Bloss (1965) and are recorded as minimum values.

‡ X = light brown; Y = Z = greenish-brown.

within the contact zone, diopside content increases, biotite grades into "vermiculite," and feldspar, where present, diminishes to zero. Within this contact zone, biotite is embayed by diopside, and the feldspar occurs as resorbed patches in optical continuity, even across boundaries of diopside grains (see pl. 1, A).

#### XENOLITHS

Nodular inclusions, which probably were once ultramafic rock and are now thoroughly altered, are scattered throughout the

biotitite core. None was encountered in the pyroxenite surrounding the biotitite. The nodules, about forty in all, are well rounded and range in diameter from 5 to 35 cm. The contact between each of them and the enclosing rock is sharp and easily recognizable in the field. The nodules persistently show three well-developed zones: (1) a core consisting of talc, dolomite, pyrite, tremolite, phlogopite, apatite, magnesite, and small amounts of quartz, listed in decreasing order of abundance; (2) an intermediate ring of tremolite and subordinate talc, pyrite, and carbonates; and (3) an outer rim composed mostly of phlogopite and interstitial dolomite, talc, and pyrite. Pyrite constitutes about 5 per cent of the core and occurs as fresh, brilliant cubes and octahedra about 0.6 mm. in diameter. The dolomite of the core is euhedral to anhedral and is much more abundant than the magnesite.

The phlogopite is very striking and occurs as elongate blades arranged radially around the nodule and normal to the sharp contact with the surrounding biotitite. This phlogopite is peculiar for its acicular habit and also for its unusual optics. The pleochroism is reversed from normal phlogopite or biotite, being  $X > Y = Z$ , X = orange brown, Y = Z = light olive-green to colorless. The other optic properties are normal with  $2V_a = 11^\circ$ ,  $n_a = 1.556$ , and  $n_g = n_r = 1.604$ . The phlogopite in the core also has reversed pleochroism, but unlike that in the rim, occurs as strongly embayed, optically continuous patches. Some of the phlogopite in the rim and core shows zoning with a center with normal optics and an irregular border with reversed pleochroism. An attempt to separate the phlogopite of the outer rim from the associated talc for chemical analyses proved unsuccessful, but a spectrographic analysis of the impure material showed no unusual constituents or concentrations of major or minor elements.

In the study of the phase equilibria of "ferriannite," Wones (1963, p. 583) reported absorption colors for the synthetic micas similar to those determined for the phlogopite

in the nodules. This led the present writer to suspect that the reversed pleochroism results from a high  $Fe^{+++}$  content in the fourfold positions of mica, and recently several authors have shared this belief. Hogarth (1964, and personal communication), in a very detailed study of the optics of micas with reversed pleochroism, related this property to a high content of tetrahedral  $Fe^{+++}$ . Rinskaya-Korsakova and Sokolova (1964) concluded that reverse pleochroism results from Al deficiency, but chemical analyses of their samples also reveal high  $Fe_2O_3$  contents.

Absorption of light in micas is believed to result from electron transfer and to be a function of the nearness of neighboring  $Fe^{++}$  and  $Fe^{+++}$  ions. Absorption would thus be greatest when the electric vector is parallel to the direction of the greatest density of  $Fe^{+++}$  and  $Fe^{++}$  ions (Hogarth, personal communication). When  $Fe^{+++}$  substitutes for Si in the tetrahedral sites, the population density of Fe would be greater in the direction normal to (001) than parallel to (001) as in normal biotites where Fe is mostly in octahedral positions. The absorption would then become  $X > Y = Z$ . Evidence in support of this interpretation can be seen in the phlogopite which shows a core with normal optics. This zoning is visible only when the cleavage traces are normal to the vibration direction of the lower nicol. When the electric vector is parallel to (001), the absorption of both zones is equal, suggesting that both have similar compositions in the octahedral layers. Also, in this position the  $Fe^{+++}$  ions in tetrahedral sites could not absorb light (exchange electrons) because  $Fe^{++}$  is absent in these positions.

These micas, although unusual, may be much more abundant than is realized, and have been noted by several previous workers. Their occurrence appears to be almost entirely restricted to carbonatites and ultrabasic rocks, although Rinskaya-Korsakova and Sokolova (1964) report some specimens from iron formations. Grains of normal phlogopite with rims showing reversed pleochroism have been reported by Wagner

(1914, p. 108) and Watson (1955, p. 56) in studies of kimberlites. Singewald and Milton (1930) describe serpentine phlogopite crystals in an alnoite pipe which are replaced by a continuous border of phlogopite with reversed pleochroism. At Alnö, von Eckermann (1948, p. 155) reports biotite with similar abnormal absorption only in deep-seated alnoites and kimberlites, and attributes this property to the effect of high pressure. Of special interest is a biotite described by Anwar (1956) which occurs in xenoliths in trachyte flows. This mica has the same pleochroic formula as that in the xenoliths at Rainy Creek and occurs "thin elongated shreds." A chemical analysis indicated 14.12 per cent  $Fe_2O_3$  and 2.9 per cent FeO.

As noted by Bowen (1928, p. 197) in his discussion of the effects of magma saturation with biotite on igneous inclusions, the melt cannot dissolve minerals higher in the reaction series, but it "can and will react with these minerals and convert them to biotite." The present writer suggests that the unusual phlogopite results when alumina-deficient ferromagnesian nodules are brought into contact with the biotite-saturated melt in a milieu of high  $pH_2O$  and  $f_{O_2}$ . Most of the Fe would be oxidized and enter the phlogopite structure; the remaining Mg would form talc, tremolite, dolomite, and magnesite. The phlogopite with normal core and reversed borders may represent the partial adjustment of earlier mica to this environment. The normal biotite in the surrounding biotitite had sufficient Al present so that  $Fe^{+++}$  was restricted to the octahedral positions.

Support for the ultrabasic parentage of the nodules are serpentine nodules, described by Pabst (1942) from a rock consisting of plagioclase, hornblende, biotite, quartz, and magnetite which he considered to be igneous. Some of these nodules have altered to talc cores surrounded by tremolite and with an outer crust of vermiculite or chlorite, which probably is weathered phlogopite.

Peter Deines, at Pennsylvania State Uni-

versity, kindly measured the isotopic composition of carbon and oxygen in dolomite from one of the nodules from the biotite. The results are  $\delta C^{13} = -10.244^3$  and  $\delta O^{18} = -18.351^3$ . These values fall near the range for carbonates from carbonatites ( $\delta O^{18} = -14$  to  $-24$  and  $\delta C^{13} = 0$  to  $-9$ ) reported by Gold (1965, p. 23) and within the range of carbon from magmatic rocks and carbonatites reported by Kukhareenko and Dontsova (1964, p. 40). The  $\delta C^{13}$  values, in addition, are significantly lower than the

dotite) which were transported to the present position by rising magma.

#### MAGNETITE PYROXENITE

The magnetite pyroxenite fits well the definition of "jacupirangite" as defined by Washington (1901) and Johannsen (1938), but this term is not used herein because in modern usage the term commonly connotes the presence of feldspathoids. This rock comprises about 42 per cent of the area underlain by the igneous complex. Some of

TABLE 5

MODES OF MAGNETITE PYROXENITES IN WEIGHT PER CENT\*

Sample	Pyr	Mt	Ap	And	Sph	Bio	Pl	Or	Location Coordinates	
M-82	64.3	29.5	6.2						N6848	E15048
M-106	71.5	21.5	6.7			0.3			N8508	E8712
M-105	66.6	18.6	4.9	10.0					N13728	E17424
M-37	68.8	25.6	5.0			0.6			N7067	E15444
M-39	64.0	28.9	7.1						N11352	E12804
MP-79	66.9	25.1	7.6			0.4			N7628	E15312
M-35	69.9	10.6	7.2		0.7	11.6			N10032	E8179
M-47	65.3	25.1	9.0			0.7			N12144	E10037
M-29	69.3	22.8	4.5	2.8	0.6				N6458	E14916
M-38	66.3	28.8	4.8		0.1				N7787	E15840
M-109	64.7	29.0	6.4						N10693	E14652
M-86	67.4	26.8	5.8						N11406	E13451
M-113	65.2	25.2	9.7						N12019	E13083
M-108	36.8	9.0	2.1		2.3	12.5	1.4	35.9	N14982	E8316
RCMD-5	58.4	8.7	1.4		0.1	31.4			N7920	E13728
RCMD-103	61.0	4.2	2.0	3.0		28.8			N7910	E13714

\* Pyr = pyroxene, Mt = magnetite, Ap = apatite, And = andradite, Sph = sphene, Bio = biotite or "vermiculite," Pl = plagioclase, and Or = orthoclase. Location coordinates are in feet north and east of the intersection of Highway 37 and Rainy Creek road. The last two samples are from magnetite pyroxenite dikes that transect the biotite pyroxenite.

range of approximately 0 to -5 in hydrothermal dolomites presented by Engel, Clayton, and Epstein (1958) and Lovering, McCarthy, and Friedman (1963).

The isotopic composition of the dolomite, together with the fact that the unusual phlogopite and the paragenesis of the nodules in the biotite core resemble the phlogopite and paragenesis of other nodules that clearly were once of ultrabasic composition, suggests that the nodules are xenoliths of Al-deficient ferromagnesian rock (e.g., peri-

\* Per mil with respect to the Chicago standard EDB-1.

this rock is fractured and friable, but enough of it is sufficiently sound and unweathered to yield samples for chemical and modal analyses. The essential minerals are clinopyroxene, magnetite, and apatite, but andradite, sphene, and biotite or "vermiculite" are common accessories. As shown in the modes in table 5, the accessories are present in various combinations and are missing in some specimens.

Much of the magnetite pyroxenite shows pronounced alignment of the pyroxene and apatite crystals. The long axes of these crystals are oriented so as to dip from the

center of the pluton at angles that range from near horizontal to near vertical. The grain size of this rock is quite uniform, ranging from about 0.7 to 3 mm. However, within about 20-50 feet from the contact with the biotite pyroxenite body, the magnetite pyroxenite is coarser grained, attaining an average size up to about 2 cm. As the rock within this contact zone is otherwise similar to the adjacent magnetite pyroxenite, it is suggested that this zone is a coarse-grained facies of that rock. This facies possibly resulted from emplacement of the magnetite pyroxenite while the biotite pyroxenite was still hot and possibly evolving volatiles, allowing slower cooling at the inner boundary. Furthermore, the incipient deuteric tremolization in the biotite pyroxenite is not manifest in the magnetite pyroxenite, but it has occurred in parts of the contact zone.

Many dikes and apophyses of magnetite pyroxenite transect the biotite pyroxenite. A photograph of a typical example of the dikes is shown in plate 2, B. The mineralogical composition of the dikes is similar to that of the main body of magnetite pyroxenite (table 5), but the latter prevalently contains more apatite and magnetite and less biotite and/or "vermiculite." Many of the dikes show a pronounced vertical banding resulting from magnetite-rich layers (pl. 2, B). The magnetite in these dikes is euhedral and appears to have crystallized early. This, together with the fact that the layers parallel the dike walls, suggests that the banding resulted from slavage differentiation (Bhat-tacharji and Smith, 1964).

The feldspar-rich magnetite pyroxenite (M-108 in table 5) is well exposed in a cut where the road crosses Rainy Creek on the northwestern side of the pluton. Pronounced vertical lamination resulting from bands rich in pyroxene, biotite, and magnetite within feldspar characterizes this rock. The pyroxene differs from that in the other pyroxenites by having borders of aegirine-augite (about  $Ac_{40}$  from optical properties) where in contact with the feldspar. The

plagioclase is albite that is present as irregular patches within the orthoclase. This rock is similar in nearly all respects to the feldspar-bearing pyroxenite at Iron Hill, Colorado, which Larsen (1942) and Temple and Grogan (1965) consider to be segregations within the main mass of pyroxenite.

A chemical analysis and norm of a sample (M-86) from the main body of magnetite pyroxenite are listed in table 6, together with an analysis of the type jacupirangite for comparison. Viewed in thin section, the magnetite pyroxenite consists of subhedral to anhedral clinopyroxene with interstitial magnetite, which embays the pyroxene and appears to postdate it. Both minerals poikilitically enclose fluorapatite prisms. Sphene and andradite, where present, are generally associated with the magnetite; sphene also forms rims or border zones on the apatite. The biotite and/or "vermiculite" occur as embayed fragments and optically continuous patches that apparently are earlier than the pyroxene. Magnetite contains lamellae of ilmenite, visible with an oil-immersion objective, which parallel the (111) planes of the host. Buddington and Lindsley (1964, p. 322) ascribe this arrangement to oxidation of ulvospinel component to ilmenite under "normal"  $f_{O_2}$  conditions. A spectrographic analysis of this magnetite is shown in table 7. It contains an unusually low MgO content and a high, although not excessive, amount of  $Cr_2O_3$  relative to that in similar pyroxenites and jacupirangites.

A chemical analysis and list of optic properties for the clinopyroxene from sample M-39 appear in table 8. Table 9 lists properties for additional pyroxenes from the magnetite pyroxenite and magnetite pyroxenite dikes. The determinative curves for the clinopyroxenes, which were discussed earlier, indicate that the atomic ratios of Fe ( $Fe^{++} + Fe^{++}:Fe^{+++} + Fe^{++} + Mg$ ) range from 19 to 22 in the pyroxenes of the main body of magnetite pyroxenite and 18 to 22 in the dikes.

The most conspicuous feature of the

magnetite pyroxenite in thin section is the island-in-sea texture produced by the strongly embayed pyroxene and the interstitial magnetite (pl. 1, B). A similar relationship occurs in magnetite pyroxenites and jacupirangites at Jacupiranga, Brazil (Melcher, 1954), Union Bay, Alaska (Ruckmick and Noble, 1959), and in thin sections of the Iron Hill, Colorado, pyroxenites examined by the writer. Fockema and

Mendelsohn (1954) report a similar arrangement between clinopyroxene and chromite. Bateman (1951) describes other examples and postulates that the ore minerals are late, remaining liquid as the result of "mineralizers" such as H<sub>2</sub>O, F, S, or phosphate. Ruckmick and Noble (1959, p. 1008) suggest that the interstitial magnetite might result from the presence of a eutectic on the magnetite side of the sys-

TABLE 6  
CHEMICAL ANALYSIS\* AND NORM OF  
MAGNETITE PYROXENITE (M-86)

	M-86	(2)†	C.I.P.W. Norm of M-86‡	
SiO <sub>2</sub>	36.89	38.38	ne	0.40
Al <sub>2</sub> O <sub>3</sub>	1.52	6.15	or	0.28
TiO <sub>2</sub>	1.52	4.32	an	2.83
Cr <sub>2</sub> O <sub>3</sub>	0.02		ab	1.47
Fe <sub>2</sub> O <sub>3</sub>	16.33	11.70	ap	6.22
FeO	8.57	8.14	il	2.88
NiO	0.00		mt	23.76
MnO	0.27	0.16	wo	4.07
MgO	10.74	11.47	di	58.30
CaO	20.60	18.60		
SrO	0.15		(wo	31.23
BaO	0.01		di	26.81
Na <sub>2</sub> O	0.26	0.78	en	0.25
K <sub>2</sub> O	0.05	0.13	Is	2.15
H <sub>2</sub> O+	0.27	0.54	D.I.	60.60
H <sub>2</sub> O-	0.00	0.18	C.I.	
P <sub>2</sub> O <sub>5</sub>	2.61	0.17		
Total	99.78	100.72		

\* Analyst: C. O. Ingamells. See table 5 for mode.

† Column (2) is an analysis of the type jacupirangite from Jacupiranga, Brazil (Washington, 1901).

‡ Norm was calculated after subtracting H<sub>2</sub>O+ and recalculating total to 99.78.

§ Spectrometric analyses by N. H. Suhr.

TABLE 7  
SPECTROGRAPHIC ANALYSIS OF  
MAGNETITE FROM MAGNETITE  
PYROXENITE\*

Al <sub>2</sub> O <sub>3</sub>	0.30
CaO	0.38
TiO <sub>2</sub>	1.7
Fe <sub>2</sub> O <sub>3</sub>	>30
Cr <sub>2</sub> O <sub>3</sub>	0.63
MnO	0.35
V <sub>2</sub> O <sub>5</sub>	0.13
MgO	0.20
Not detected: Ni, Cu, Sr, Ba, Zr	

\* Analyst: N. H. Suhr.

tem diopside-magnetite. However, Presnall (1966) showed that the join diopside-magnetite intersects the divariant surface separating the diopside and spinel primary phase volumes at 21 weight per cent magnetite at about 1,300° C. in air atmosphere to f<sub>0<sub>2</sub></sub> = 10<sup>-6</sup> atm. At f<sub>0<sub>2</sub></sub> = 10<sup>-8</sup> atm., magnetite is not stable on this join. It was not determined if a reaction relationship exists between diopside and magnetite at this point. It must be noted, however, that lower temperatures and the presence of volatiles may alter these conclusions.

Of interest is the observation that, in the magnetite pyroxenite dikes, magnetite occurs as early euhedral to subhedral crystals enclosed by clinopyroxene (pl. 1, C). A similar relationship was noted in some of the border rocks at Union Bay by Ruckmick and Noble (1959, p. 1004), who consider crystallization in these rocks to have been rapid. The present writer suggests that early crystallization of magnetite in the dikes resulted from a higher f<sub>0<sub>2</sub></sub> than in the main body, as Hamilton, Burnham, and Osborn (1964) have shown experimentally that a relatively high f<sub>0<sub>2</sub></sub> favors earlier separation of magnetite from basaltic melts. The dikes may also have formed under a higher f<sub>0<sub>2</sub></sub>, as suggested by the abundance of hydrous minerals.

Excluding the samples which contain feldspar or abundant biotite or "vermiculite," the magnetite pyroxenite contains 21.5–29.5 weight per cent magnetite. This, when compared with the range of 22–29 per cent reported by Irvine (1959, p. 185) in the pyroxenites in southeastern Alaska and the position of the point on the diopside-magnetite join at 21 weight per cent magnetite determined by Presnall (1966), lends added support to an igneous origin for these rocks at Rainy Creek. Metasomatic origins have been proposed for similar rocks by many investigators in other complexes.

#### ORIGIN

The gross structural, mineralogic, and chemical features of the Rainy Creek pluton

TABLE 8  
CHEMICAL ANALYSIS\* AND OPTIC PROPERTIES  
OF CLINOPYROXENE (P-103) FROM  
MAGNETITE PYROXENITE

Analysis		Cations on the Basis of 6 Oxygens	
SiO <sub>2</sub>	51.59	Si	1.914
Al <sub>2</sub> O <sub>3</sub>	1.86	Al <sup>IV</sup>	0.081
TiO <sub>2</sub>	0.61		2.00
Cr <sub>2</sub> O <sub>3</sub> †	<0.02	Cr	
Fe <sub>2</sub> O <sub>3</sub>	2.86	Fe <sup>+++</sup>	0.080
FeO	3.26	Fe <sup>++</sup>	0.101
MnO	0.18	Mn	0.006
MgO	14.67	Mg	0.811
CaO	24.35	Ca	0.967
NiO	0.00	Na	0.021
Na <sub>2</sub> O	0.29	K	0.002
K <sub>2</sub> O	0.05	Ti	0.017
SrO†	0.14	Sr	0.003
BaO†	<0.01	Ba	
H <sub>2</sub> O-	0.01	O	6.000
Total	99.87		6.00
n <sub>a</sub> = 1.692 ± 0.001		Perfect (100) parting	
n <sub>β</sub> = 1.698 ± 0.001		Hand specimen is dark green	
n <sub>γ</sub> = 1.717 ± 0.001		Faintly pleochroic	
2V <sub>γ</sub> (calculated) = 62.0°		Irregular zoning	
2V <sub>γ</sub> (measured) = 58°		Occasional opaque exsolution lamellae parallel to (100) and (001)	
Z∧C = 42° – 44°			

\* Analyst: C. O. Ingamells.

† Spectrometric analyses by N. H. Suhr.

strongly suggest that the biotite pyroxenite, biotite, and magnetite pyroxenite were derived by differentiation from a common parent magma. The biotite occupies a central position near the highest point in the ultramafic pluton, and it also represents a marked concentration of alkali metals, metal sulfides, and volatiles relative to the surrounding pyroxenite. Therefore, this writer proposes that H<sub>2</sub>O existed as a separate phase and accumulated, along with alkali metals and sulfides, near the roof of the magma chamber in the region of lowest temperatures and pressures. The alkaline pegmatites within the biotite suggest that

H<sub>2</sub>O existed as a separate phase, at least in the late stages of crystallization. Whether diffusion alone could produce such large gradients in the distribution of H<sub>2</sub>O is problematic. Perhaps circulation of magma in thermal-convection cells could augment diffusion by bringing H<sub>2</sub>O-rich magma from depth to the top of the chamber. Convection cells of the type illustrated by Shaw (1965, p. 148) for granitic magmas would be particularly effective, even more so in basic melts because of lower viscosity.

Kennedy (1955, p. 489) states that "Water will diffuse and distribute itself in a magma so that the chemical potential of

TABLE 9

## PROPERTIES OF CLINOPYROXENES FROM MAGNETITE PYROXENITES\*

Rock Sample	Indices $n_a$ , $n_b$ , $n_c$ $\pm 0.001$	Optic Angle	Average $Z \wedge C$	FeO†	FeO‡	Accessory† Minerals
M-36.....	1.692 1.698 1.717	58°	43°	3.26	2.86	N
Sp-51.....	1.691 1.698 1.717	59°	43°	3.47	2.24	B A
M-105.....	1.693 1.701 1.721	59°	44°	4.67	3.15	A
M-40.....	1.692 1.700 1.719	58°	44°	3.72	3.02	S B
M-82.....	1.690 1.697 1.716	61°	44°	3.99	1.95	N
M-106.....	1.691 1.698 1.717	60°	44°	4.50	2.41	N
RCMD-103.....	1.694 1.701 1.721	57°				B A
P-43.....	1.687 1.694 1.711	63°				B F

\* The last two pyroxenes are from dikes of magnetite pyroxenite.

† FeO and FeO<sub>2</sub> analyses by C. O. Ingamells.

‡ Every rock contains clinopyroxene, magnetite, and apatite in addition to the indicated accessory minerals: N = none, B = biotite or "vermiculite," A = andradite, S = sphene, and F = feldspar.

the water is the same throughout the magma chamber. By this mechanism water tends to be concentrated in the magma chamber in the regions of lowest pressures and temperatures. Alkalies and certain metals will coordinate with the water and, similarly, be concentrated in the regions of lowest pressure and temperature." However, this mechanism does not appear to be applicable to these rocks. Hamilton *et al.* (1964) have shown experimentally that the solubility of H<sub>2</sub>O in mafic magmas increases with total pressure. In addition, the temperature effect on the solubility of H<sub>2</sub>O (Soret effect) in melts of the composition of the Rainy Creek rocks is unknown. Furthermore, that alkalies and other metals would co-ordinate with H<sub>2</sub>O (hydroxyl) in solution seems improbable.

According to Wones and Eugster (1965, p. 1264), the ratio  $Fe^{+++}:Fe^{++} + Fe^{++}$  of biotite provides a rough estimate of  $f_{O_2}$ - $T$  conditions during crystallization. This ratio in biotites RCB-12 and RCSp-55 is 0.21 and 0.24, respectively, which is close to the value 0.25 reported by Wones and Eugster for biotite that crystallized under  $Fe_3O_4$ - $Fe_2O_3$  buffer conditions. Stability curves for these two biotites, based on  $KFe^{++}AlSi_3O_{10}(OH)_2$  contents, were calculated from equation (6') of Wones and Eugster and are shown in figure 4. Curves 1 and 2 suggest, with crystallization under  $Fe_3O_4$ - $Fe_2O_3$   $f_{O_2}$ - $T$  conditions, a maximum temperature of crystallization of the biotite of about 850° C. for  $f_{H_2O}$  less than 5 kb. At this temperature, the  $f_{O_2}$  of the buffer is  $10^{-8}$  atm. (Eugster and Wones, 1962, p. 92).

In the system  $CaSiO_3$ - $MgO$ -iron oxide- $SiO_2$  at a total pressure of 1 atm., Presnall (1966) showed that with fractional crystallization at a constant  $f_{O_2}$  of 0.21 atm., and perhaps as low as  $10^{-6}$  atm., simple olivine pyroxenite liquids can yield magnetite pyroxenites. Presnall's results at  $f_{O_2} = 10^{-8}$  atm. are shown in figure 2. The content of the components of this system in the analyses of the pyroxenites (tables 1 and 6), together with an analysis of the magnetite pyroxenite by Larsen and Pardee (1929),

is plotted in figure 2 after subtracting the CaO present in apatite and recalculating to 100 per cent. These rocks are treated in this simple tetrahedron to illustrate that they may have originated from a common parent magma. A direct analogy between crystallization in the synthetic system and in the proposed parent magma is impossible, particularly because biotite, rather than olivine, is present in the pyroxenites. It is suggested, however, that the addition of volatiles and alkalies to this system will create a primary field for phlogopite, perhaps at the expense of olivine.

In figure 5, point 1 plots within the primary volume of olivine. With fractional crystallization at a constant  $f_{O_2}$ , cooling to the liquidus temperature would precipitate olivine, and the remaining melt would change composition away from Mg-rich olivine toward point *a*. At this point, Mg-rich diopside crystallizes with the olivine, and the liquid proceeds to point *c*. The diopside has become progressively richer in Fe. In the vicinity of point *X'*, olivine would dissolve in the liquid with equilibrium crystallization in a  $CO_2$  atmosphere and at  $10^{-9.68}$  atm.  $f_{O_2}$ ; there are insufficient data to indicate whether the reaction relationship persists at  $f_{O_2}$  as low as  $10^{-6}$  atm. Nevertheless, with fractional crystallization, the liquid leaves the boundary curve and follows an oxygen isobar on the diopside-magnetite-liquid surface toward point 2, precipitating diopside and magnetite. With perfect fractional crystallization, the liquid would continue to the silica-magnetite-diopside-liquid boundary curve, but with imperfect fractional crystallization, the liquid would not reach the temperature minimum and may or may not precipitate additional phases, depending upon bulk composition. Thus, in the synthetic system, fractional crystallization has produced olivine pyroxenites followed by magnetite pyroxenites, and the pyroxenes become enriched in Fe.

In the case of fractional crystallization under fixed bulk composition (decreasing  $f_{O_2}$ ), Presnall's data are less complete in

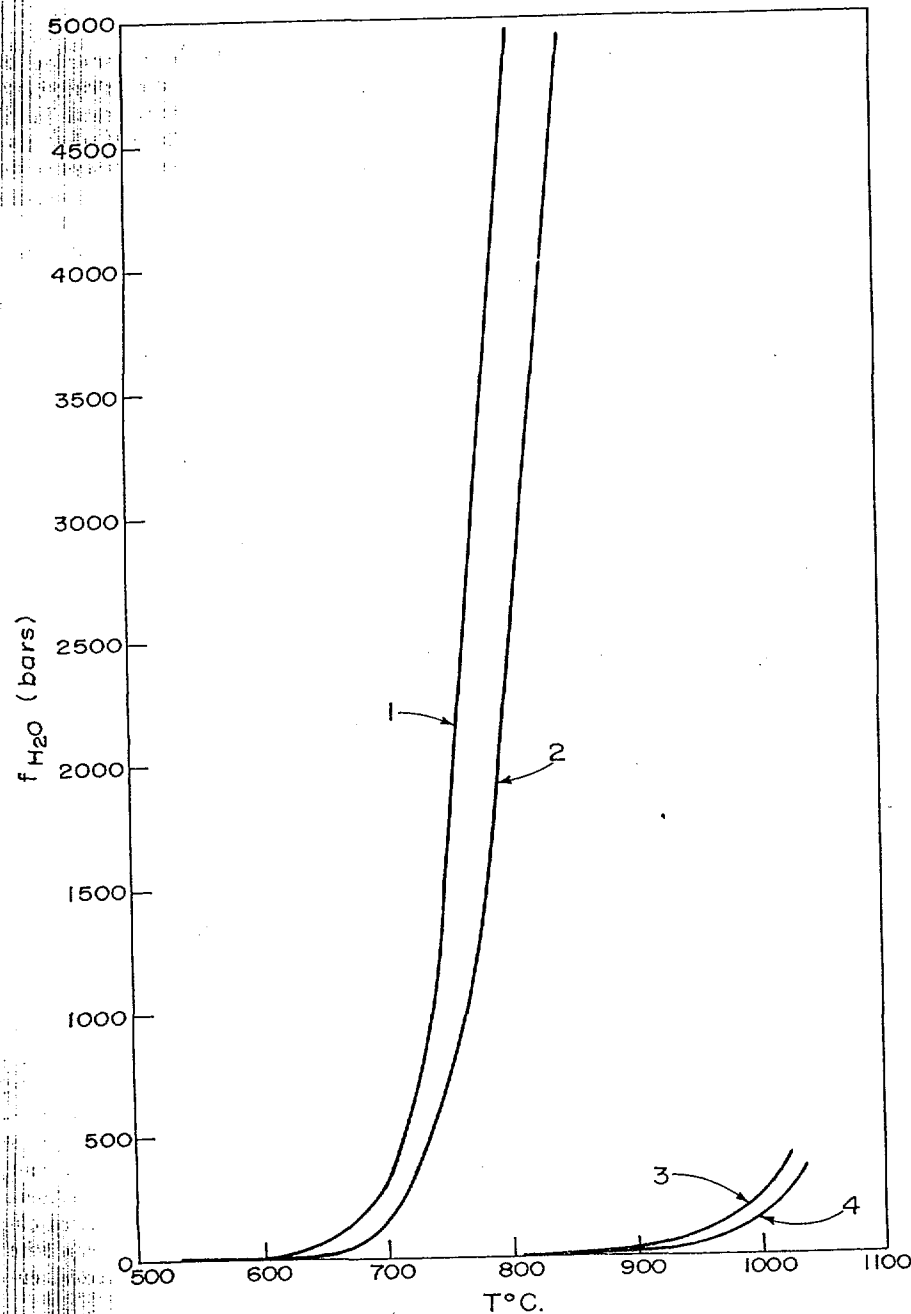


FIG. 4.—Stability curves of biotites. The curves were calculated from equation (6') of Wones and Eugster (1965). Curves 1 and 2 represent the stability of RCB-12 and RCB-55, respectively, coexisting with magnetite and hematite. Curves 3 and 4 represent the stability of RCB-12 and RCB-55, respectively, coexisting with quartz, magnetite, and fayalite.

that they provide no confirmation that the reaction relationship of olivine persists as it does with equilibrium crystallization at high  $f_{O_2}$ . If the reaction relationship does persist, however, the sequence of crystallization in the early stages would be the same if the magnetite field boundary is reached. It is considered unlikely that similar assemblages could be obtained by fractional fusion of olivine pyroxenites (Presnall, 1966). In addition, with fractional fusion, the magnetite pyroxenite would be generated first,

and this conflicts with the field evidence at Rainy Creek, if the order of emplacement is also the sequence of magma generation.

Pyroxenes from the biotite pyroxenite and magnetite pyroxenite contain little Al relative to similar rocks, for example, those from Magnet Cove and Iron Hill. In LeBas's (1962, p. 275) diagram of  $Al_2O_3$  against  $SiO_2$ , Kushiro's (1960, p. 549) diagram of Al against Si, and Challis' (1965, p. 350) diagram of  $Al_2$  against Si, the pyroxenes from both pyroxenites plot far within the

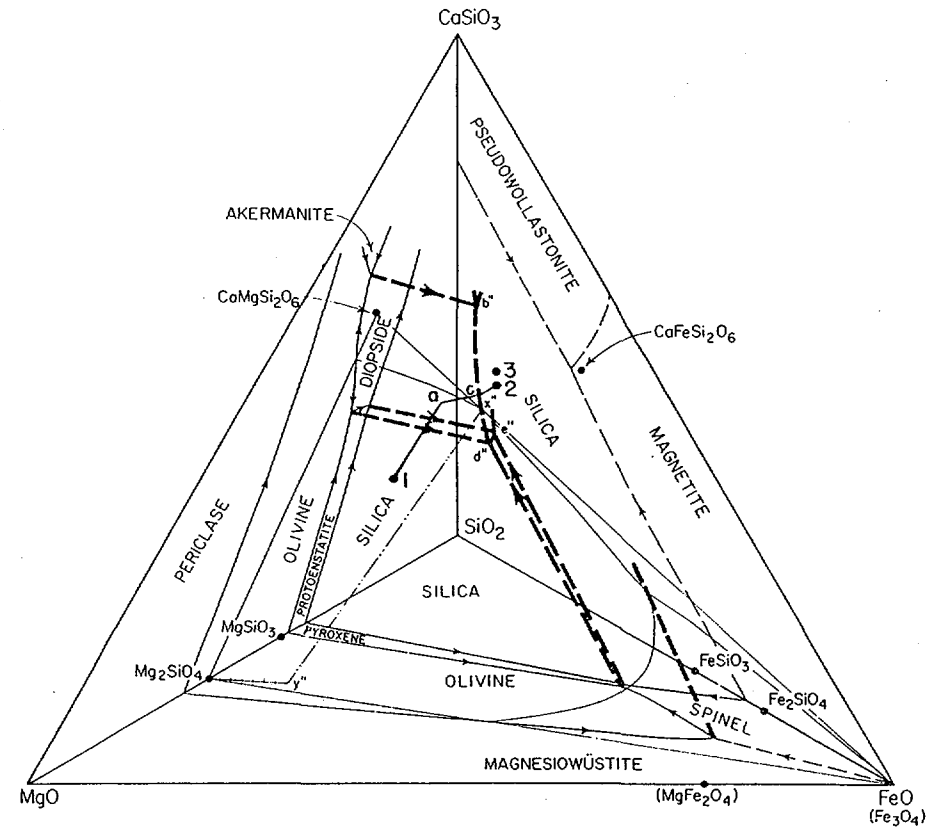


FIG. 5.—Crystallization of pyroxenites in the system  $CaSiO_3$ - $MgO$ -iron oxide- $SiO_2$ . Points 1, 2, and 3 represent, respectively, biotite pyroxenite RCB-64, magnetite pyroxenite M-86, and magnetite pyroxenite (Larsen and Pardee, 1929, p. 103). Point X'' is the intersection of the diopside-magnetite join with the boundary curve along which liquid coexists with olivine, clinopyroxene, and magnetite. Area d''b''e'' represents the plane along which liquid coexists with clinopyroxene and magnetite. Point a lies on the plane separating the primary fields of clinopyroxene and olivine. Modified after Presnall's (1966, p. 769) diagram of  $f_{O_2} = 10^{-8}$  atm.

tholeiitic (Al-poor) fields. Similarly, these pyroxenes plot with those from the Red Hills and Dun Mountain dunites and the Bushveld, Stillwater, and Skaergaard complexes in Challis' (1965, p. 352) diagram of  $Al_2$  against  $Na$ . Hess (1960) suggests that high pressures favor higher Al contents in clinopyroxenes, but Hytönen and Schairer (1961) have prepared diopsides with over 10 per cent  $Al_2O_3$  at 1 atm. total pressure. To account for the low Al contents of the Rainy Creek pyroxenes, it is suggested that biotite separated early in the biotite pyroxenite and biotitite, resulting from high  $p_{H_2O}$ , thus fractionating Al from the pyroxenite melt, also effectively purging most of this element from the residual melt from which the magnetite pyroxenite crystallized. Such a mechanism also would fractionate K, thereby explaining the low  $K_2O$  content of the magnetite pyroxenite relative to that of the biotite pyroxenite. Experimental data on the crystallization of biotite clinopyroxenites are lacking, but Luth (1963) has investigated the system  $KAlSiO_4-Mg_2SiO_4-SiO_2-H_2O$  and has shown that phlogopite is stable at liquidus temperatures at  $p_{H_2O}$  as low as 2 kb. These results are not directly applicable, however, because phlogopite is stable to higher temperatures than biotite.

The high magnetite content of the magnetite pyroxenite considerably increases the  $FeO$  and  $Fe_2O_3$  content and reduces the  $SiO_2$  and  $MgO$  content relative to that of the biotite pyroxenite. Consequently, misleading results are obtained when analyses of these rocks are plotted on most variation diagrams. For example, on the curves employed by Osborn (1959, p. 634; 1962, p. 223), such as the one plotting  $FeO + Fe_2O_3$  against  $SiO_2$ , the Rainy Creek pyroxenites plot with a large negative slope similar to the Skaergaard liquids. Such curves, therefore, fail to distinguish between rocks that contain magnetite and those that have undergone strong Fe enrichment of the ferromagnesian silicates. Similarly, when the analyses are plotted against the differentiation index (Thornton and Tuttle, 1960) or the crystallization index (Poldervaart and

Parker, 1964), the curves for  $FeO$ ,  $Fe_2O_3$ , and  $MgO$  follow the trends of most other differentiated suites, whereas the curves for  $SiO_2$ ,  $Al_2O_3$ , and  $K_2O$  are reversed.

More meaningful and revealing results are obtained from plots of the crystallization trends of the pyroxenes shown in figure 3. Also shown in figure 3 are the pyroxene trends of two highly differentiated teschenite sills, the Japanese alkaline basalt series and the Skaergaard gabbros. Clinopyroxenes from Duke Island, Alaska (Irvine, 1963) and Union Bay, Alaska (Rucknick and Noble, 1959) plot similarly to those from Rainy Creek, but the latter are much poorer in Al. Both of the teschenite sills contain abundant magnetite—4 to 10 per cent in the Garbh Eilen sill (Murray, 1954, p. 25) and 6 to 15 per cent in the Black Jack sill (Wilkinson, 1958, p. 10). Osborn (1959, 1962) considers the Skaergaard trend toward strong Fe enrichment of the residual liquids as an indication that fractional crystallization has occurred at constant bulk composition (decreasing  $f_{O_2}$ ). That is, the liquids do not remain on the magnetite-diopside surface (plane  $d''e''b''$  in fig. 5) after the appearance of magnetite, but, rather, they leave this surface and continue in the direction of Fe enrichment. The two teschenite sills, on the other hand, appear to have crystallized under a more nearly constant  $f_{O_2}$ , where "the  $O_2$  isobaric surface on which the liquid must remain intersects this magnesioferrite [magnetite] surface, and hence the fractionating liquid cannot slide down the magnesioferrite roof and continue to increase in iron content" (Osborn, 1959, p. 628). The addition of  $CaSiO_3$  (Presnall, 1966),  $CaAl_2Si_2O_8$  (Roeder and Osborn, 1966), or up to 5 weight per cent  $TiO_2$  (Speidel, 1964) to the system  $MgO-FeO-Fe_2O_3-SiO_2$  (Muan and Osborn, 1956) does not alter this conclusion.

Although the Rainy Creek pyroxenites have followed a similar trend, the magnetite-diopside surface was reached while the pyroxene was Fe-poor diopside, and enrichment of Fe in the pyroxenes was slight after the appearance of magnetite (fig. 6). Pres-

## IGNEOUS COMPLEX NEAR LIBBY, MONTANA

nall (1966) demonstrated that, with increasing  $f_{O_2}$ , the magnetite-diopside surface moves toward diopside and away from the "FeO" apex. These data suggest that the Rainy Creek pyroxenites crystallized at a  $f_{O_2}$  higher than that in the hypabyssal teschenite sills and at a  $f_{O_2}$  which was more nearly constant or even increasing. Presnall's work was conducted at temperatures much higher than those proposed herein, and the Rainy Creek rocks probably crystallized under lower  $f_{O_2}$  than described in the above experimental data.

In conclusion, it is suggested that the biotite pyroxenite and the later magnetite pyroxenite are derived from a common parent magma, but at different times. The magnetite pyroxenite likely was emplaced

as a hotter and dryer magma than was biotite pyroxenite, and, for this reason, does not appear to be a product of differentiation of the biotite pyroxenite; that they are not linearly related.

### FENITE

The fenite at Rainy Creek is exposed in two exploration pits near the northern contact of the magnetite pyroxenite with Belt Series. The fenite is a replacement of the Wallace formation, but the exact nature of the original rock is unknown. Unaltered rock at approximately the same elevation about 1,000 feet north of the fenite calcareous siliceous argillite. No other exposures have been encountered during study. However, Larsen and Pardee (1

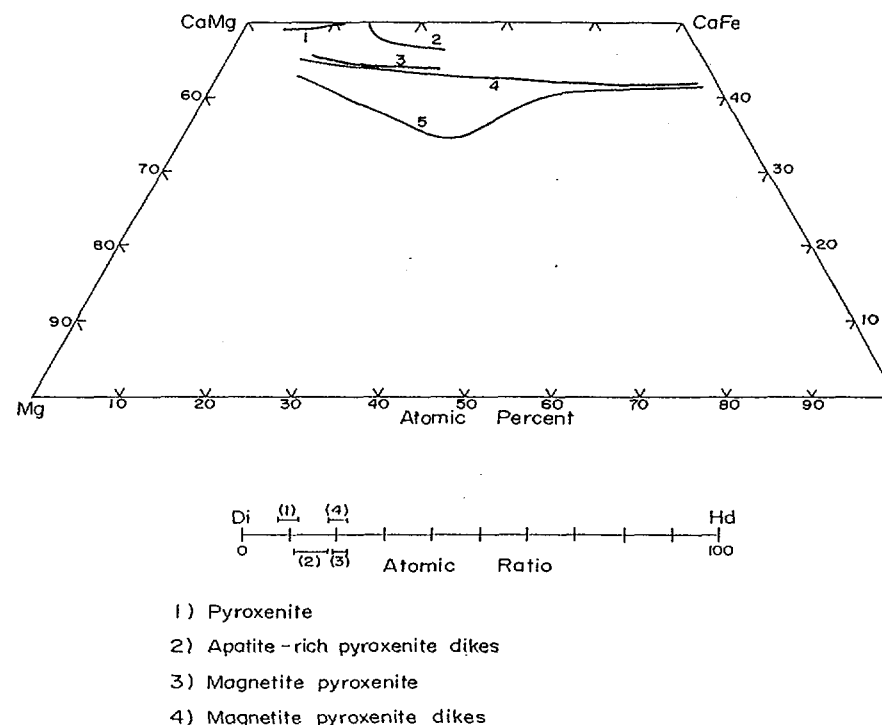


FIG. 6.—Crystallization trends of pyroxenes: 1, Rainy Creek pyroxenites; 2, Black Jack teschenite (Wilkinson, 1957); 3, Garbh Eilen teschenite sill (Murray, 1954); 4, Japanese alkaline basalt series (A 1964); and 5, Skaergaard pyroxenes (Brown and Vincent, 1963). Below, the atomic ratios of the Rainy Creek pyroxenes ( $Fe^{+++} + Fe^{++} : Fe^{+++} + Fe^{++} + Mg$ ) are projected on the diopside-hedenbergite join.



p. 108) describe a "syenite" exposed in an adit at approximately the same location near the northern boundary, made up of coarse-grained perthite cut by numerous "streaks and veinlets" of aegirine-augite. The adit is now inaccessible, but their petrographic descriptions and the location strongly suggest that the "syenite" is fenite.

The fenite discovered by the present writer is zoned, changing in mineralogical and chemical composition outwardly from the contact with the pluton. Near the contact, it is a dense, light-gray to yellow rock composed mostly of microcline and containing black porphyroblasts of garnet. Oriented

TABLE 10  
SPECTROGRAPHIC ANALYSIS OF  
SCHORLOMITE FROM  
FENITE\*

SiO <sub>2</sub> .....	27
Al <sub>2</sub> O <sub>3</sub> .....	1.4
CaO.....	28
MgO.....	1.50
TiO <sub>2</sub> .....	9 ± 1
"Fe <sub>2</sub> O <sub>3</sub> ".....	25
Cr <sub>2</sub> O <sub>3</sub> .....	0.019
MnO.....	0.37
V <sub>2</sub> O <sub>5</sub> .....	0.18
Not detected: Ni, Cu, Sr, Ba	
$a = 12.12 \pm 0.02 \text{ \AA}$	

\* Analyst: N. H. Subr.

biotite produces a near-vertical foliation. The microcline is turbid, and all sections show incipient to moderate muscovitization. The garnet constitutes 20 to 25 per cent of the fenite and occurs as euhedra up to 1.5 cm. in diameter. Two varieties are present; one is yellow andradite and the other is dark red-brown to black schorlomite with faint oscillatory zoning. Both are totally isotropic. A spectrographic analysis of the schorlomite is shown in table 10. Note should be given to the high TiO<sub>2</sub> content. Both MnO and V<sub>2</sub>O<sub>5</sub> are appreciable. The andradite is persistently associated with sphene, the two forming aggregate pseudomorphs after schorlomite and accompanied by subordinate magnetite, which formed from the breakdown of schorlomite (pl. 1, D). The biotite in this fenite occurs mostly

as resorbed fragments partially replaced by schorlomite and associated with scattered magnetite. Sphene and apatite are common accessories. Some specimens contain a few irregular patches of granophyric intergrowths of potash feldspar and quartz.

Fenite was also observed in a pit 20 feet from the rock described above, in a direction away from the igneous center. This fenite is thinly laminated, the nearly vertical layers of aggregates of biotite, red-brown garnet, and aegirine-augite alternating with layers rich in potash feldspar and muscovite. Sphene and apatite are common accessories; magnetite is present in minor amounts. The aegirine-augite appears to be replaced by the biotite. All of the garnet is associated with the biotite, commonly in small grains which encircle aggregates of biotite. The proportion of garnet decreases outward, and it contains less Ti than schorlomite as indicated by  $a = 12.08 \pm 0.02 \text{ \AA}$ . No breakdown of the garnet to andradite was noted.

The exact sequence of changes in the argillites during fenitization is difficult to establish from petrographic data. Most of the biotite appears to be a transitory phase, replacing pyroxene but breaking down to garnet with advancing fenitization. The absence of aegirine-augite and the presence of garnet in the inner fenite zones may be the result of higher temperatures or the absence of sufficient Na. The breakdown of schorlomite to andradite and sphene appears to be retrogressive. The absence of this reaction in the garnet that contains less Ti away from the contact suggests that, with decreasing temperature, the solubility of Ti is reduced, thus occasioning the breakdown. The alteration of potash feldspar resembles that described in the Alnö fenites (von Eckermann, 1948, p. 31) in the "zone of maximum hydration."

Goranson (1927) analyzed aegirine-augite from the "syenite" (fenite) collected by Larsen. The high TiO<sub>2</sub> content of this pyroxene (2.57 per cent), together with the abundance of schorlomite and sphene, indicates that the fenites are rich in Ti. Although an evaluation of the chemical

changes during fenitization must await further work, it is concluded that Fe<sup>+++</sup>, K, Ti, and P were introduced, and Si and perhaps Na were removed. Although these metasomatic rocks are similar to those surrounding other alkaline complexes and carbonatites, the abundant garnet at Rainy Creek is atypical, being reported previously only at Alnö (von Eckermann, 1948) and Semarule, Bechuanaland (King and Sutherland, 1960). Furthermore, the abundant introduction of K and removal of Na, although noted at Alnö, is uncommon. The K has been added only in small amounts at many areas and has even been removed at Spitzkop, Transvaal (Strauss and Truter, 1951) and Oka, Quebec (Gold, 1964). Saether (1957) reports that the ratio of Na:K in fenites is a function of the composition of the invaded host rock, but this does not appear to be true in all cases. For example, Garson (1962, p. 51) writes that "The end product of fenitization at Tundulu [Malawi] is essentially the same whatever the original composition of the rock." Dawson (1964, p. 111) states that the presence or absence of quartz in the host will influence the nature of the fenitization, but this will not explain the differences at, for example, Alnö and Spitzkop where in both cases the invaded rock is quartz-feldspathic. Part of the differences in the ratio of K:Na may perhaps be explained by the findings of Orville (1963) that the composition of a vapor phase coexisting with two feldspars is a function of temperature and Ca content of the feldspars.

The least known and most important aspect of fenitization is the source of the fenitizing ions. In the words of King and Sutherland (1960, p. 521), "A fenitized envelope is present whether the complex consists of silicate rocks only, silicate rocks and carbonatites, or carbonatites alone. The source of the fenitising agencies is thus problematic." More recently, Dawson (1964, p. 107-108) has presented strong evidence in support of his conclusion that "carbonate bodies themselves are the source of the fenitisation ions." On the basis of the results

of investigations at similar complexes, the present writer suggests that the fenitizing fluids at Rainy Creek did not emanate from any of the exposed rocks, and this is regarded as the best evidence for the existence of carbonatite or alkaline rocks, such as ijolite at depth.

#### CONCLUSIONS

Surface exposures of the Rainy Creek district are considered to represent the upper part of the igneous complex; volcanic activity may or may not have been present at former higher levels. The similarities of this complex to other alkaline centers, particularly those associated with carbonatite, together with the presence of fenite, suggest that carbonatite, alkaline rocks, or both exist at depth. Further evidence for this suggestion may derive from the work of Temple and Grogan (1965) at Iron Hill, Colorado. They suggest that vertical movement along a major fault exposed rocks of lower levels that include carbonatite, uncomphagrite, and garnetiferous ijolite, whereas those in the upper levels include biotite-rich and feldspar-bearing pyroxenites, magnetite-perovskite rock (including pyroxenites), and garnet-poor ijolite. All of the pyroxenites have similar counterparts at Rainy Creek.

The assumption that nepheline syenites are indicative of nearby carbonatite is widespread in the literature. However, Smith (1956, p. 208) concluded that pyroxenite and ijolite, not nepheline syenite, are the rocks "most commonly associated with carbonatites." Similarly, Tomkeieff (1961, p. 747) states that "in respect of the finding of carbonatite deposits, the most important criterion will be the presence of nepheline-pyroxene rocks of metasomatic origin, associated with pyroxenites and peridotites."

Although the Rainy Creek complex appears to contain less titania and much more phosphate than similar bodies, this in part may be only a reflection of the erosional level and outcrop pattern. The phosphate is concentrated mostly in the magnetite pyroxenite, in accord with the observation of

Pecora (1956, p. 1547) that in alkaline complexes which contain both biotite pyroxenes and carbonatite, phosphorous is concentrated in an intermediate rock type consisting of biotite, magnetite, apatite, ferromagnesian silicates, and other minerals. Titania, on the other hand, is concentrated in the fenites, trachytes, pegmatites, and certain syenites at Rainy Creek and may be more abundant at depth. Furthermore, the K:Na ratio of the Rainy Creek rocks appears to be higher than in many similar complexes, but Moore (1962), in a study of Cenozoic igneous rocks of the western United States, suggested that this ratio is more a function of geographic location than of age or internal processes.

Many investigators have proposed that peridotite or carbonated alkali peridotite (King and Sutherland, 1960) is the primary parent of alkaline-ultramafic rock associations. In experiments on the melting of peridotites at pressures greater than 15 kb. (Green and Ringwood, 1964), the primary field of orthopyroxene increases with pressure. This implies that fractional melting of peridotite could move the melt into the field of critically undersaturated alkali basalts or, as predicted by Holmes and Harwood (1932) and Powers (1935), early separation of hypersthene could impoverish the residual melt in silica. Tilley and Yoder (1964) question whether excessive amounts of orthopyroxene could remain without accompanying amounts of clinopyroxene; they nevertheless conclude that extraction of pyroxenes leads to undersaturation. If continued melting to higher temperatures puts pyroxene into the melt, it may precipitate as the melt cools during the rise toward the surface, again producing undersaturated melts. Crystal settling could occasion separation of crystals, particularly in view of the fact that alkaline complexes are restricted to the stable platforms and shield areas. During rapid rise of a magma, as might be expected under orogenic conditions, crystallization would occur at higher levels and

lower pressures where olivine might be the primary phase and the residual melt would not be undersaturated. Reay and Harris (1964) have demonstrated that partial fusion of peridotite at low pressure (1 atm.) produces a melt with normative hypersthene or hypersthene plus quartz. Because of the large melting interval of alkali basalts at high  $f_{H_2O}$  (Yoder and Tilley, 1962, p. 452), O'Hara (1965) suggested that the melting of natural peridotite would yield silica-rich liquids. However, the experimental work of Hamilton *et al.* (1964) demonstrated that  $f_0$ , in a mafic magma greatly affects the melting interval and order of crystallization. Further work with buffered charges may strengthen the possibility that partial fusion of peridotites may produce melts capable of precipitating alkaline-ultramafic rocks. Such experiments will be of particular importance if the parent magma is carbonated.

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